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VIBRATIONAL STUDIES OF THE STRUCTURE OF DISORDERED  
SOLIDS(U) XEROX PALO ALTO RESEARCH CENTER CA  
F L GALEENER 14 MAR 84 N00014-80-C-0713

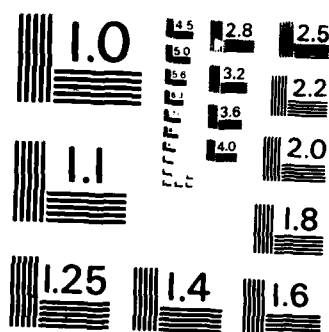
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FINAL REPORT  
to the  
OFFICE OF NAVAL RESEARCH

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Contract Number: N00014-80-C-0713

Title: Vibrational Studies of the  
Structure of Disordered Solids

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SUMMARY

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The goal of this program was to "further improve our understanding of the vibrational excitations of disordered solids, and to use this knowledge to elucidate the structure of glasses and amorphous thin films". Much significant progress has been made, utilizing Raman, infrared and inelastic neutron scattering experiments, supplemented by novel theoretical work on central force network models and dihedral angle averaged Bethe lattices. Particularly important were the discovery of regular rings of bonds as dominant defects in the otherwise disordered structure of amorphous  $\text{SiO}_2$ , and the unveiling of simple Raman selection rules for amorphous networks. Twenty two scientific papers have been published, and several more are in the process of completion. The results have excited much interest, as evidenced by the presentation of eleven invited talks on contract work.

Most of the experimental effort was carried out on bulk glasses, including  $\text{SiO}_2$ ,  $\text{GeO}_2$ ,  $\text{GeS}_2$ ,  $\text{B}_2\text{O}_3$ ,  $\text{B}_2\text{S}_3$ ,  $\text{BeF}_2$  and  $\text{ZnCl}_2$ . This was done to develop a fundamental understanding of several network topologies, using materials whose properties are relatively insensitive to details of preparation, and which can be obtained as large samples for neutron scattering. Enough work was done on thin films ( $\text{SiO}_2$ ,  $\text{Si}_3\text{N}_4$ ,  $\text{Nb}_2\text{O}_5$  and  $\text{Ta}_2\text{O}_5$ ) to establish the experimental methods for a new study - of process induced defects in amorphous insulating films.

The present report includes a list of the published papers, a list of the invited talks and a discussion of the highlights of the reported results.

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## A. HIGHLIGHTS

The work carried out under contract N00014-80-C-0713 will be described under six headings as follows. (Publications under the contract are listed in the reference section preceded by the letter C.)

### I THE THEORY OF VIBRATIONS IN AMORPHOUS NETWORKS

Thorpe and Galeener [C1] generalized the methods of Sen and Thorpe [1] to enable calculation of band limits for the vibrations of amorphous networks with topologies other than the one appropriate for  $\text{SiO}_2$ . The new method uses coordinate systems which are defined by the covalent bond directions at every individual atom, and thus avoids the coordinate rotations that would otherwise be required in treating a glass with respect to a laboratory frame of reference. The overdetermination that often results is handled easily by a Lagrangian mechanics formulation. The central role of the connectivity matrix of the network is revealed. Expressions for band limits are obtained for numerous topologies, and experiments have been carried out on several examples. This paper provides the framework for treating other topologies and for adding refinements such as non-central forces and long-range coulomb forces.

Galeener and Thorpe [C20] next extended this work to treat networks involving small regular rings of bonds, like those in  $\text{v-B}_2\text{O}_3$ . In particular, band limit formulas were obtained for an  $\text{A}_2\text{X}_3$  network consisting of regular puckered six-membered  $\text{A}_3\text{X}_3$  rings. For the special case of planar "boroxol" rings in  $\text{v-B}_2\text{O}_3$ , this theory shows much improved agreement with experiment over a model not containing rings. The remaining discrepancies illustrate the need to include non-central forces in the network dynamics of rings. This paper demonstrated, for the first time, how increased intermediate range order (in the form of regular rings) gives rise to new features in the vibrational density of states of a glassy network.

Barrio, Galeener and Martinez [C22] have used insight gained from this work to develop a new scheme for including non-central forces. It appears that one cannot obtain band edge limits in the simple algebraic form of [C1] and [C20], but one can develop relatively simple computer techniques for calculating the vibrational density of states (VDOS) of an infinite

network having "arbitrary" homogeneous topology. The problem is made "simple" by performing an analytical average over the dihedral angles ( $\phi_1$ ) in the network on the assumption that the  $\phi_1$  are random and uncorrelated. The resultant " $\phi$ -averaged Bethe lattice" provides a very good fit to the Raman spectra of  $v\text{-SiO}_2$  and  $v\text{-GeO}_2$  (including non-central forces) and is being exploited to treat network and defect vibrations in other amorphous solids. We believe this will be a particularly valuable tool for treating the vibrations of defects in amorphous solids.

Payne and Inkson [2] have very recently used results from [C1] in order to incorporate the coulomb forces that are required to explain the TO-LO splittings reported [3] in  $v\text{-SiO}_2$  and  $v\text{-GeO}_2$ . At least two other groups are working on related treatments of the TO-LO problem.

Much of this was reviewed in an article by Galeener entitled "Phonons in Glasses" [C9].

## II VIBRATIONAL SELECTION RULES IN AMORPHOUS SOLIDS

The only way to determine empirically the vibrational selection rules in a disordered solid is to measure directly (if possible) the vibrational density of states (VDOS), then see which probes (Raman, ir, tunneling spectroscopy, etc.) respond strongly to particular features in the VDOS. Galeener et al. [C3], have obtained a good measure of the VDOS of  $v\text{-ZnCl}_2$  from measurement of the inelastic neutron scattering spectrum, and compared it with the polarized Raman spectra that were measured. Galeener, Leadbetter and Stringfellow [C16] have made a much more complete study of  $v\text{-SiO}_2$ ,  $v\text{-GeO}_2$  and  $v\text{-BeF}_2$ . They find that the HV Raman spectrum mimics the VDOS but the HH spectrum does not, indicating the presence of strong frequency-dependent matrix elements in the HH Raman response. This corroborates the idea that the HH Raman spectrum selects out a relatively small number of states having a very special SS (symmetric stretch) symmetry, as first predicted in Ref. 4. If these results can be shown to be general, they will be of considerable practical importance in the study of amorphous thin films where inelastic neutron scattering is extremely difficult compared to Raman scattering. In one effort to test generality, inelastic neutron scattering experiments have been planned (with collaborators) on amorphous solids having other topologies, like  $v\text{-B}_2\text{O}_3$ .

Some aspects of generality have been tested by theoretical work, as follows. Martin and Galeener [C4] have applied the Wolkenstein bond polarizability model to the central force model for vibrations in  $\text{SiO}_2$ -like glasses [1, C1] and successfully interpreted the aforementioned empirical selection rules. The dominant Raman line in the HH spectrum is shown to be due to in-phase motion of the bridging oxygen atoms along the bisector of the angle they subtend with their two nearest neighbours. This strong result was extended by Galeener [C7] to other glass topologies, and has been applied to interpretation of anomalous features such as the sharp "defect" lines seen in the HH Raman spectrum of  $v\text{-SiO}_2$  [C8, C11]. Martin and Galeener [C4] were able to give a heuristic argument why the HV Raman spectrum should mimic the VDOS, but this empirical observation has not yet been proven mathematically.

Various aspects of the work on vibrational selection rules have been discussed by Galeener in a short review article entitled "Raman Studies of Glass Structure" [C10] and in a more extensive review, "Vibrational Probes of Glass Structure" [C12].

### III THE EFFECTS OF ISOTOPIC SUBSTITUTION ON AMORPHOUS NETWORK DYNAMICS

Several experiments were carried out involving the complete substitution of one isotope of an element for another isotope. In an isotopic substitution one changes only the masses, leaving the glass structure and force constants (chemistry) unchanged. This provides a crucial test of the theories developed in I (above) and, having validated the vibrational theories, can provide evidence concerning the structure of the glasses studied.

Galeener and Mikkelsen [C6] carried out the first such substitution in  $v\text{-SiO}_2$ : thick films ( $\sim 10 \mu\text{m}$ ) of amorphous  $\text{Si}^{18}\text{O}_2$  were formed by steam oxidation of Si in  $\text{H}_2^{18}\text{O}$ , and high S/N polarized Raman spectra were obtained from these films. All of the peaks were observed to shift to lower frequencies with the change to  $^{18}\text{O}$  from the natural (lighter)  $^{16}\text{O}$ . The shifts of these broad features were well-predicted by the central force continuous random network (CF-CRN) model [1, C1], as applied to  $\text{SiO}_2$ -like glasses by Galeener [4]. The two sharp "defect" lines were found to shift as though there were little or no Si motion involved in those two modes.

Galeener and Geissberger [C17] performed a high precision test of these results by obtaining the Raman spectra of  $v\text{-SiO}_2$  before and after the substitution  $^{28}\text{Si}$ - $^{30}\text{Si}$ . While the shifts of the other broad lines were still well-predicted by the CF-CRN model, the dominant Raman line was found to have a small discrepancy, which was explained in terms of an effect of disorder which cannot be included in the CF only models of [C1]. The Raman active "defect" lines  $D_1$  and  $D_2$  exhibited no Si mass dependence, which greatly restricted the defect structures that can be considered for their origin. It was concluded that the absence of Si motion is inconsistent with all previous (broken-bond and wrong-bond) models for  $D_1$  and  $D_2$ , but is consistent with the recent assignment of  $D_1$  and  $D_2$  to modes of highly ordered (planar) rings of bonds [C11]. These rings will be discussed a bit more in Section IV (below).

Galeener, Geissberger, Ogar and Loehman [C10] reported the  $^{16}\text{O}$ - $^{18}\text{O}$  and  $^{70}\text{Ge}$ - $^{74}\text{Ge}$  isotope shifts in the Raman spectra of  $v\text{-GeO}_2$ . The shifts of the broad features compared well with CF-CRN theory, as was the case for  $v\text{-SiO}_2$ . The narrow "defect" line at  $530\text{ cm}^{-1}$  appears to involve no Si motion and was tentatively identified with a regular ring of bonds. The other narrow line, at  $345\text{ cm}^{-1}$ , is unique in that it consists largely of Ge motion, for which no satisfactory model has yet been proposed.

To explore the ring hypothesis, Galeener and Geissberger [C13] carried out Raman studies of  $^{10}\text{B}$ - $^{11}\text{B}$  isotopic substitution in  $v\text{-B}_2\text{O}_3$ , where planar 3-rings are virtually certain to exist. Two modes were found to exhibit no B isotope shifts. The broad one at  $450\text{ cm}^{-1}$  was assigned to the SS of oxygen atoms bridging between rings, while the sharp one at  $808\text{ cm}^{-1}$  is widely believed to be due to a SS breathing mode of the boroxol ring. This work showed empirically that the signature of a regular ring embedded in an otherwise amorphous network is the existence of an isolated, sharp, highly polarized line which shows little or no cation (B) isotope shift. This has served to strengthen the earlier assignment of the  $D_1$  and  $D_2$  lines to regular rings in  $v\text{-SiO}_2$  [C8, C11].



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#### IV INTERMEDIATE RANGE ORDER IN GLASSES

Much of the work described in I and II (above) enabled explanation of the dominant broad features seen in the Raman and infrared spectra of several glasses in terms of the short range order or nearest neighbour environment of the glass. But short range order alone proved incapable of explaining the sharper features observed in such glasses as  $v\text{-SiO}_2$  [4],  $v\text{-B}_2\text{O}_3$  [5] and  $v\text{-As}_2\text{O}_3$  [6]. Galeener [C8, C11] has proposed that these sharp lines are evidence for intermediate range order, in the form of regular (often planar) rings of bonds. An energy minimization argument was devised which predicts that very small rings of bonds are expected to be planar (and therefore regular) even when they are embedded in an otherwise disordered network. On this basis, the  $606\text{ cm}^{-1}$   $D_2$  "defect" Raman line in  $v\text{-SiO}_2$  was assigned [C8] to the existence of - 1% of planar hexagon-like (3-fold) rings. It was also shown that planar 2-fold rings (edge sharing tetrahedra) required too much energy for formation, and this was also the case for cage-like structures (face sharing tetrahedra; adamantane-cages).

The energy minimization argument was refined in a subsequent paper by Galeener [C11], where it was concluded that the  $D_1 = 495\text{ cm}^{-1}$  line was very probably due to a regular but slightly puckered 4-ring. The  $D_1$  and  $D_2$  frequencies were shown to correspond nicely to breathing modes of 4-rings and 3-rings, respectively, which have been observed in cyclo-silicate minerals [C11] and in cyclo-siloxane molecules [C14]. In [C11], larger concentrations of regular rings (of specific orders) were predicted in numerous other glasses including  $v\text{-BeF}_2$ ,  $v\text{-GeO}_2$ ,  $v\text{-GeSe}_2$  and  $v\text{-As}_2\text{O}_3$ . Empirical evidence in support of these predictions is growing.

The theoretical work of Galeener and Thorpe [C20] mentioned in Section I (above) is a first effort to understand the dynamics of the atoms in regular rings embedded in a disordered host network. Moderate success was achieved in understanding the  $^{10}\text{B}$ - $^{11}\text{B}$  isotope shifts reported in [C13], and the discrepancies were confidently ascribed to the lack of non-central forces. This means that proper treatment of the regular rings requires inclusion of both central and non-central forces in the problem.



Geissberger and Galeener [C15] have extended the ring studies to a previously unsynthesized glass,  $v\text{-B}_2\text{S}_3$ . by comparison of the Raman spectra of this glass with those of a known crystalline form, they concluded that the glass contains both 2-fold and 3-fold planar rings of B-S bonds. This was the first known case of 2-fold rings in a glass; however, similar 2-rings have now been reported in  $v\text{-SiS}_2$  [7].

Much of the work concerning regular rings in glasses has been discussed in a review by Galeener, entitled "Vibrational Evidence for Intermediate Range Order in Glasses" [C14].

## V APPLICATIONS OF VIBRATIONAL SPECTROSCOPY TO GLASS SCIENCE

These activities have in common the development of Raman spectroscopy as a monitor for the effects of various aspects of environment (or sample history) on the properties of  $v\text{-SiO}_2$ .

It was pointed out quite some time ago by Galeener and Geils [8] that the strongly polarized well-isolated Raman line seen in vitreous  $\text{SiO}_2$  at  $3700\text{ cm}^{-1}$  could be used to accurately measure "water" concentration in fused silica. Exploiting this, Galeener and Mikkelsen [C5] have developed non-destructive techniques which enable the profiling of OH in fused silica. Spatial resolution of  $\sim 50\text{ }\mu\text{m}$  was achieved, and order-of-magnitude improvements were confidently predicted. It is likely that some other diffused impurities can be profiled this way, and there would seem to be applications for the study of weathering, corrosion, etc. The results of [C5] have recently been used in Great Britain by groups concerned with the degradation of undersea fibre optic cables [9].

Geissberger and Galeener [C18] have completed a detailed study of the Raman spectra of  $v\text{-SiO}_2$  as a function of sample fictive temperature  $T_f$  for  $900^\circ\text{C} < T_f < 1550^\circ\text{C}$ . These observations were made: (1) the broad features (network lines) change frequency in a manner consistent with densification by reduction of the average Si-O-Si angle  $\theta$ ; (2) the sharp "defect" lines  $D_1$  and  $D_2$  show little or no shift in frequency; (3) both defect line intensities exhibit Arrhenius behaviour,  $\exp(-\Delta E/k_B T_f)$ , with well-defined activation energies  $\Delta E$  of 0.14 and 0.40 eV respectively. It was found that these observations do not change with OH concentration, but that the rate of relaxation of structure at a new annealing temperature depends strongly on

temperature and on the OH concentration. These observations contain more information about the network and defect structure of  $v\text{-SiO}_2$  (as well as structural relaxation processes) than we presently know how to understand. Nevertheless, the behaviour of the  $D_1$  and  $D_2$  lines is completely consistent with the ring models introduced in [C8] and [C11].

Galeener, Geisberger and Weeks [C21] have utilized the information obtained above [C18] to gain insight into the geological origin of Libyan Desert glass (LDG), which is about 98% pure  $\text{SiO}_2$ . LDG shows polarized Raman spectra that are virtually identical to those of pure  $v\text{-SiO}_2$ . The time-temperature dependence of the  $D_2$  "defect" lines in LDG was studied and then used to infer information about the thermal history of a pristine sample of the natural glass. It was concluded that the LDG could not have cooled from the melt in seconds, nor did it cool from high temperatures over geological periods of time. This suggested that the samples of LDG were not ejecta, that they were not quenched in rapid flight from either a volcanic event or a meteor impact.

## VI RAMAN SPECTROSCOPY OF INSULATING THIN FILMS

Galeener, Stutius and McKinley [C2] developed a special sample manipulator, enabling them to launch a guided wave in a thin film, image the path of the (wave-guided) laser beam onto the entrance slit of a Raman spectrometer, and obtain polarized Raman spectra from the thin film guide. The long path length thus sampled enabled acquisition of high signal to noise spectra ( $S/N \sim 1000/1$ ) and should facilitate the study of thin film growth-induced defects by Raman scattering. The first Raman spectra of amorphous sputtered  $\text{Nb}_2\text{O}_5$ ,  $\text{Ta}_2\text{O}_5$ , and CVD-deposited  $\text{Si}_3\text{N}_4$  were thus obtained and reported [C2]. Preliminary analysis suggested that the Nb and Ta are orthogonally six-coordinated to O atoms, while the N lies at the center of an equilateral triangle of (tetrahedrally-coordinated) Si atoms. This interpretation is supported by the more sophisticated machinery that has been developed in this research program. It now appears that we have developed sufficient theoretical tools to enable exploitation of this experimental method in our forthcoming studies [10] of process induced defects in insulating thin films.

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10. A proposal entitled "Defects in Amorphous Insulators" is in preparation, to be submitted to the ONR.

C. PUBLICATIONS UNDER CONTRACT N00014-80-C-0713

- C1 "Network Dynamics"  
M.F. Thorpe and F.L. Galeener  
Phys. Rev. B 22, 3078 (1980).
- C2 "Electron Microscopy and Raman Spectroscopy of  $\text{Nb}_2\text{O}_5$ ,  $\text{Ta}_2\text{O}_5$ , and  $\text{Si}_3\text{N}_4$  Thin Films"  
F.L. Galeener, W. Stutius and G.T. McKinley  
in the Physics of MOS Insulators, eds. G. Lucovsky, S.T. Pantelides and F.L. Galeener, (Pergamon, New York, 1980), p. 77.
- C3 "Raman and Inelastic Neutron Scattering by Vitreous  $\text{ZnCl}_2$ "  
F.L. Galeener, J.C. Mikkelsen, Jr., A.C. Wright, R.N. Sinclair, J.A.E. Desa and J. Wong  
J. Non-Cryst. Solids 42, 23 (1980).
- C4 "Correlated Excitations and Raman Scattering in Glasses"  
R.M. Martin and F.L. Galeener  
Phys. Rev. B 23, 3071 (1981).
- C5 "Raman Diffusion Profilometry: OH in Vitreous  $\text{SiO}_2$ "  
F.L. Galeener and J.C. Mikkelsen, Jr.  
Appl. Phys. Lett. 38, 336 (1981).
- C6 "Vibrational Dynamics in  $^{18}\text{O}$ -Substituted Vitreous  $\text{SiO}_2$ "  
F.L. Galeener and J.C. Mikkelsen, Jr.  
Phys. Rev. B 23, 5527 (1981).
- C7 "Vibrational Selection Rules in Disordered Solids: Vitreous  $\text{GeO}_2$ "  
F.L. Galeener  
J. Phys. (Paris) 42(C6), 24 (1981).
- C8 "Planar Rings in Vitreous Silica"  
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J. Non-Cryst. Solids 49, 53 (1982).
- C9 "Phonons in Glasses"  
F.L. Galeener  
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- C10 "Raman Studies of Glass Structure"  
F.L. Galeener  
in Raman Spectroscopy, Linear and Nonlinear, eds. J. Lascombe and P.V. Huong, (Wiley Hayden, Chichester, 1982), p. 529.
- C11 "Planar Rings in Glasses"  
F.L. Galeener  
Solid State Commun. 44, 1037 (1982).
- C12 "Vibrational Probes of Glass Structure"  
F.L. Galeener  
Kinam, 4(C), 83 (1982)  
CIFMD (Mexican Government) Workshop.

- C13 "Raman Studies of  $B_2O_3$  Glass Structure:  $^{10}B$ - $^{11}B$  Isotopic Substitution"  
P.L. Galeener and A.E. Geissberger  
J. Phys. (Paris) 44(C9), 343 (1983).
- C14 "Vibrational Evidence for Intermediate Range Order in Glasses"  
P.L. Galeener  
in the Structure of Non-Crystalline Materials II, eds. P.H. Gaskell,  
A.E. Davis and J.N. Parker, (Taylor and Francis, London, 1983), p. 337.
- C15 "Raman Studies of Vitreous  $B_2S_3$  and Polycrystalline  $(HBS_2)_3$ "  
A.E. Geissberger and P.L. Galeener  
in The Structure of Non-Crystalline Materials II, eds. P.H. Gaskell,  
A.E. Davis and J.N. Parker, (Taylor and Francis, London, 1983), p. 381.
- C16 "A Comparison of the Neutron, Raman and Infrared Vibrational Spectra of  
Vitreous  $SiO_2$ ,  $GeO_2$  and  $BeF_2$ "  
P.L. Galeener, A.J. Leadbetter and M.W. Stringfellow  
Phys. Rev. B 27, 1052 (1983).
- C17 "Vibrational Dynamics in  $^{30}Si$ -Substituted Vitreous  $SiO_2$ "  
P.L. Galeener and A.E. Geissberger  
Phys. Rev. B 27 6199 (1983).
- C18 "Raman Studies of Vitreous  $SiO_2$  Versus Fictive Temperature"  
A.E. Geissberger and P.L. Galeener  
Phys. Rev. B 28, 3266 (1983).
- C19 "Vibrational Dynamics in Isotopically Substituted Vitreous  $GeO_2$ "  
P.L. Galeener, A.E. Geissberger, G.W. Ogar, Jr., and R.E. Loehman  
Phys. Rev. B 28, 4768 (1983).
- C20 "Rings in Central Force Network Dynamics"  
P.L. Galeener and M.F. Thorpe  
Phys. Rev. B 28, 5802 (1983).
- C21 "On the Thermal History of Libyan Desert Glass"  
P.L. Galeener, A.E. Geissberger and R.A. Weeks  
J. Non-Crystalline Solids (in press).
- C22 "The Vibrational Bethe Lattice with Random Dihedral Angles"  
R.A. Barrio, P.L. Galeener and E. Martinez  
Phys. Rev. Letters (in press).

D. INVITED TALKS (BY F.L. GALEENER)  
UNDER ONR CONTRACT N00014-80-C-0713

- T1 "Network and Defect Vibrations in Glasses"  
Annual Meeting of the American Ceramic Society  
Washington, D.C., May, 1981.
- T2 "Applications of Raman Spectroscopy to the Elucidation of Glass Structure"  
Sixth University Conference on Glass Science  
Pennsylvania State University  
University Park, PA, July, 1981.
- T3 "Phonons in Glasses"  
NATO Adv. Study Institute on Excitations in Disordered Solids  
Michigan State University  
E. Lansing, MI, August, 1981.
- T4 "Vibrational Probes of Glass Structure"  
Amorphous Silicon Workshop  
Centro Internacional de Fisica y Matematicas Orientados  
Cuernavaca, Morelos, Mexico, January, 1982.
- T5 "Raman Selection Rules in Halide Glasses"  
First Int'l. Symposium on Halide and Other Non-Oxide Glasses  
Cambridge University  
Cambridge, England, March, 1982.
- T6 "Vibrational Evidence for Intermediate Range Order in Glass Structure"  
Int'l. Conference on the Structure of Non-Crystalline Materials II  
Cambridge University  
Cambridge, England, July 1982.
- T7 "Raman Studies of Glass Structure"  
Eighth Int'l. Conference on Raman Spectroscopy  
Universite de Bordeaux  
Bordeaux, France, September, 1982.
- T8 "Regular Rings in Glasses"  
American Physical Society March Meeting  
Los Angeles, March, 1983.
- T9 "Raman Studies of Regular Rings in Glasses"  
Int'l. Symposium on Structure and Bonding in Non-Crystalline Solids  
Reston, VA, May, 1983.
- T10 "On the Thermal History of Libyan Desert Glass"  
Int'l. Conference on Glass in Planetary and Geological Phenomena  
Alfred, NY, August, 1983.
- T11 "Raman Studies of the Thermal History of Insulating Glasses"  
Int'l. Conference on the Modes of Formation of Glass  
Vanderbilt University  
Nashville, TN, July, 1984.

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